RESPONSE OF SOIL BULK DENSITY AND MINERAL NITROGEN TO HARVESTING AND CULTURAL TREATMENTS

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Abstract-The interactive effects of harvest intensity, site preparation, and fertilization on soil compaction and nitrogen mineralization were examined in a loblolly pine (*Pinus taeda* L.) stand growing on a sandy, well-drained soil in eastern Texas. The experimental design was 2 by 2 by 2 factorial, consisting of two harvesting treatments (mechanical whole-tree and hand-fell boles only removed), two site preparation treatments (bedded and unbedded), and two fertilization treatments (fertilized and unfertilized). Soil bulk density was measured before and after harvesting and site preparation, Ion exchange resin bags located at the bottom of soil columns were used to monitor nitrogen mineralization rates in the upper 15 centimeters of soil during the first two growing seasons following harvesting. The mechanical treatment had no effect on soil bulk density at 0 to 5 and 10 to 15 centimeter depths but significantly increased it at 20 to 25 centimeters. Bedding reduced soil bulk density at 10 to 15 and 20 to 25 centimeter depths. The mechanical treatment removed 16 percent more biomass and 127 percent more nitrogen than the hand-fell treatment, but had no affect on nitrogen-mineralization rates. Bedding significantly increased both total mineral nitrogen and nitrate formation during the first growing season but had no effect during the second year. The increase in mineral nitrogen due to the bedded preparation was equal to the increase in mineral nitrogen following application of 250 kilograms per hectare of diammonium phosphate. The results suggest that logging slash and other surface biomass has little influence on nitrogen-mineralization for the first two years after harvesting unless there is considerable soil disturbance and/or incorporation of the surface organic matter.

INTRODUCTION

Declining productivity with successive rotations has been reported for *Pinus radiata* in south Australia (Keeves 1966), *Pinus patula* in Swaziland, Africa (Evans 1978), *Pinus radiata* in New Zealand (Whyte 1973), and *Pinus taeda* and *P. elliottii* in Louisiana, USA (Haywood 1994) raising concerns over the sustainability of current intensive management practices (Powers 1990, Powers and others 1996). In 1989, the USDA Forest Service initiated a series of nationwide studies of long-term soil productivity (LTSP) on the National Forest System (Powers 1990). To complement and extend the LTSP program to industrial forests, a cooperative effort among forest industries, universities, and the U.S. Department of Agriculture was begun in 1993 (Powers and others 1996). This cooperative effort, known as MPEQ for "Monitoring Productivity and Environmental Quality in Southern Pine Plantations," has research installations in four locations in the Southern United States. This is one of the first in a series of reports from this cooperative effort.

Harvesting promotes nutrient losses from forest ecosystems through biomass removal (Kimmins 1977, Tew and others 1986) and increased nutrient mineralization in the soil (Likens and others 1970). Whole-tree harvesting and short rotations accentuate such losses (Switzer and others 1978, Stevens and others 1995). Nitrogen is especially susceptible to losses during harvesting and regeneration (Vitousek and Melillo 1979). Since nitrogen is one of the most limiting factors in many forest ecosystems (Keeney 1980), nitrogen (N) availability is considered an index of soil fertility and soil productivity (Powers 1980). Tew and others (1986) reported that complete-tree harvesting of a 22-year-old loblolly pine (*Pinus taeda* L.) plantation on a Piedmont site in North Carolina removed twice as much N as stem-only harvesting, while Vitousek and Matson (1985) found that harvesting and site preparation increased soil nitrate formation significantly.

Soil compaction caused by harvesting equipment (Guo and Karr 1988, Guo and others 1990) may reduce future forest productivity (Powers and others 1996) unless this compaction is mitigated. Site preparation by bedding improves soil internal drainage increasing survival and/or growth of pine seedlings on poorly drained and moderately well-drained soils (Ducan and Terry 1983, Tiarks 1983, Gent and others 1986, Mckee and Wilhite 1986). On drier sites, bedding can cause moisture stress by channeling water away from seedling root zones (Broeman and others 1983). Mounding and concentrating the surface horizon by bedding could mitigate compaction resulting from harvesting traffic, but the soil disturbance incurred by bedding could also increase nutrient mineralization.

The objectives of the study reported here were to determine the effects of standard operational practices on soil compaction and N availability *on* a sandy, well-drained soil in the gulf coastal plain of eastern Texas.

MATERIALS AND METHODS

The study site is located in Tyler County, TX, on the property of Temple Inland Forest Products Company. The soil belongs to the Besner series, a coarse-loamy, siliceous, thermic Typic Glossudalf. At time of harvest in August 1994, the site was occupied by a stand of loblolly pine direct-seeded in 1968 and thinned in corridors at age 15 years. There have been at least three harvests of loblolly pines on this site and no history of cultivation. Other characteristics of the stand and soil are shown in table 1.

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Table I-Characteristics of the loblolly pine plantation at the time of harvesting

Characteristics	Block A	Block B	Block C
Age	26	26	26
Site index (meters, 25 years)	i7.i	17.4	17.5
Stand density (stems per hectare)	1962	1625	1805
Basal area (square meters per hectare)			
Pine	29.6	25.1	29.4
Hardwood	2.7	2.3	2.5
Volume[a] (cubic meters per hectare)			
Pine	246.5	221.2	255.8
Hardwood	21.0	21.2	18.9
Overstory biomass[a] (tons per hectare)			
Pine	115.1	101.7	120.7
Hardwood	11.2	11.8	10.1
Understory biomass (tons per hectare)	5.3	12.1	14.0
Litter biomass (tons per hectare)	24.3	17.7	17.5
Soil carbon: 0 to 15 centimeters (pct)	1.075	1.058	1.422
Soil nitrogen: 0 to 15 centimeters (pct)	0.038	0.030	0.045
Soil CEC: 0 to 15 cm (meq per gallon)	0.725	0.688	0.638
Soil pH: 0 to 15 centimeters	4.9	5.0	4.8

[a] Volume and biomass equations for pine from Baldwin (1987), for hardwood from Clark and others (1985).

Prior to harvesting, three experimental blocks were established. Each block was divided into eight 42- by 28-meter (0.12 hectare) plots. On each plot, height and diameter at breast high (d.b.h.) were recorded for all trees > 5 centimeters d.b.h. Four 1- by 2-meter subplots were established in each main plot. All vegetation < 5 centimeters d.b.h. was clipped, weighed, and subsampled for moisture determination and elemental analysis. The litter was also weighed, subsampled, and returned to the laboratory for analysis. Three dominant and codominant pines were felled on each plot for stem analysis. Starting at groundline, a disc was removed every 0.5 meters for 10 meters and every 1 meter from 10 meters to the tip. From the 0-, 5-, and 1 O-meter discs, a 22.5-degree wedge was removed. Wood and bark were separated, dried, ground, and cornposited for elemental analysis.

Soil samples for elemental analysis were collected from four locations on each plot at depths of 0 to 10 centimeters, 10 to 20 centimeters, and 20 to 30 centimeters. Soil bulk density was determined in June 1994, 1 month before harvesting, and in May 1995, 9 months after harvesting. Volumetric samples were taken at four locations on each plot at depths of 0 to 5 centimeters; 10 to 15 centimeters; 20 to 25 centimeters. The volumetric samples were dried at 105°C to a constant weight.

Harvesting was conducted July 25 through August 5, 1994. The mechanical whole-tree treatment (MWT) employed a 600 series Hydro-Ax feller-buncher with a rotary cutter and three rubber tire skidders. All merchantable pine (and most unmerchantable pine and hardwoods) were felled, bunched, and skidded to the loading deck where they were delimbed and topped. On the hand-felled boles only (HFB) plots, merchantable pine were felled with chainsaws, delimbed, and topped in place. Merchantable boles were lifted from the plots by a loader positioned outside the plot.

On September 20, 1994, the entire harvested area was treated aerially with a mixture of imazapyr and triclopyr (0.5 plus 2.0 kilograms per hectare). Bedding was performed on October 17 and 18, 1994, with a Savannah stump-jump plow on a D-7 tractor. The site was planted with improved 1-O loblolly pine seedlings in February 1996. On May 6, 1996, DAP was broadcast by hand.

Nitrogen mineralization was monitored in soil columns enclosed in an uncovered, polyvinyl chloride tube with a package of mixed-bed ion exchange resin (IER) at the bottom (Binkley and Matson 1983, Hart and Binkley 1985). Binkley (1984) suggested this technique was most appropriate for field estimation of both N-mineralization and transport. We further confirmed that no further transformation or removal of NH,' or NO,' occurred once adsorbed by the IER.

The 5- by 30-centimeter tubes, beveled on the lower rim, were driven into the soil approximately 15 centimeters and carefully removed. Approximately 1 .O centimeter of soil was removed from the bottom of the tube and replaced with a bag of resin. The tube was then returned to the hole. IER bags contained 8 grams of Fisher No. R276-500 plus a perforated plastic disc about 5.1 centimeters in diameter. Both disc and resin were wrapped in nylon mesh. Bags were assembled and stored frozen until transported to the field in a cooler. Four tubes were placed in each plot. The incubations were conducted May 15, 1995 to November 9, 1995 and May 17, 1996 to November 12, 1996. Resin bags were replaced approximately every 8 weeks during these periods, To determine ambient levels of mineral N, soil samples were collected with a push-tube adjacent to the incubation tubes at the beginning and end of each incubation period.

Mineral N was determined by the same methods for both soil and resin. Ten grams of soil (or 8.0 grams of resin) were placed in 80 mililiters two nitrogen potassium chloride (a 20-gram sample of soil was dried at 105°C for moisture determination), Extractions were shaken at approximately 275 revolutions per minute for an hour, allowed to settle for an hour, filtered, and stored at 4°C until analyzed. Ammonium and nitrate N were determined with Alltech's Ammonia Analyzer system. Net N mineralization was determined by subtracting initial (May) soil mineral-N (NH,+ + NO;) from the sum of final (Nov) soil mineral-N plus mineral-N captured by IER bags.

Since fertilizer was not applied until May 6, 1996, the statistical model for the 1995 N-mineralization data was an unbalanced 2 by 2 factorial. Soil bulk density after harvesting and site preparation was subjected to analysis of covariance with bulk density before harvesting as the covariate. Unless indicated otherwise, all significant difference refers to $\alpha=0.05$.

RESULTS

MWT harvesting did not alter soil bulk density at 0 to 5 centimeters or 10 to 15 centimeters but significantly ($p<0.005$) increased it at 20-25 cm depth (table 2). Bedding did not change soil bulk density in the first 5 centimeters from the surface but reduced it 10 to 15 centimeters ($p<0.001$) and 20 to 25 centimeters ($p<0.001$) soil depths (table 2). However, the crests of the beds were 15 to 30 centimeters above the original soil surface datum. Thus, the stratum at 20 to 25 centimeters from the crest of the beds is not comparable to the stratum sampled at that depth on the unbedded plots. In the near term, bedding appears to have increased the volume of low density soil available for root growth, but a zone of soil compacted during harvesting may still remain.

Assuming all aboveground components of merchantable pine (d.b.h. > 15 centimeters) were removed from the MWT plots while only boles of merchantable pine were removed from the HFB plots, MWT harvesting removed 16 percent more biomass and 127 percent more N than was removed by HFB harvesting (table 3). To verify this assumption, three MWT and three HFB plots were selected and residue biomass determined on the same 1- by 2-meter subplots used in the original biomass sampling. Actual residue differed from estimated residue by less than 5 percent although the coefficient of variations among subplots was quite high.

However, the large differences in nitrogen-rich residue remaining on the HFB plots did not result in a detectable difference in mineral N in the soil during the first two growing seasons following harvest (tables 4 and 5). Conversely, bedded soils were approximately 30 percent higher in mineral N than unbedded soils (table 4). And more mineral N was captured in the resin bags from bedded soil during the May/July monitoring period of the

Table 2-Mean soil bulk density by depth in May 1995 after harvesting in August 1994 and bedding in October 1994 (adjusted by covariance bulk density determined before harvesting)

Harvest method	Not bedded	Bedded	Mean[a]
Soil depth: 0 to 5 centimeters			
Hand fell, boles only	1.11	1.21	1.16a
Mechanical whole tree	1.26	1.19	1.22a
Mean[a]	1.18a	1.20a	
Soil depth: 10 to 15 centimeters			
Hand fell, boles only	1.31	1.17	1.24a
Mechanical whole tree	1.39	1.13	1.26a
Mean[a]	1.35a	1.15b	
Soil depth: 20 to 25 centimeters			
Hand fell, boles only	1.38	1.28	1.33b
Mechanical whole tree	1.49	1.31	1.40a
Mean[a]	1.44a	1.30b	

[a] Means in the same column or row within depths followed by different letters are significantly different ($p<0.05$).

Table 3—Estimated[a] biomass and nitrogen (N) removal by mechanical whole tree (MWT) and hand-fell, boles only (HFB) harvesting based on removal of all pine with d.b.h. > 15 centimeters

Factor measured	MWT	HFB	Difference
			Percent
Total aboveground biomass (tons per hectare)	148	160	-08
Biomass removal (tons per hectare)	92	78	+16
Total aboveground N (kilograms per hectare)	402	462	-13
Nitrogen removal (kilograms per hectare)	134	59	+127

[a] Volume and biomass equations for pine from Baldwin (1987), for hardwood from Clark and others (1985).

Table 4-Ambient mineral N content of upper 15 centimeters of soil in May 1995 after harvesting in August 1994 and bedding in October 1994

	Site preparation		
Harvest method	Not bedded	Bedded	Mean[a]
	-------*Kilograms per hectare*-------		
Hand-fell, boles only	59.8	79.2	69.7a
Mechanical whole tree	65.1	81.1	73.1a
Mean[a]	62.5b	80.2a	

[a] Means within the same column or row followed by different letters are significantly different ($p<0.05$).

first growing season. But after the middle of the first growing season, differences due to bedding were not detected after the July 1995 sampling (table 5).

Application of diammonium phosphate resulted in an increase of 8 to 10 kilograms per hectare mineral N moving through the soil profiles in the sampling tubes, and the increase was consistent across both harvesting and site preparation treatments (table 5). But even with the addition of mineral N fertilizer, the amount of soil mineral N during the second growing season appeared to be below that of the first.

DISCUSSION

Increased soil bulk density at 20 to 25 centimeter depth following mechanical harvesting but not at 0 to 5 or 10 to 15 centimeters was observed on the MPEQ site in north Louisiana as well as in the present study.[2] The relatively high organic matter content of the upper soil strata may offer sufficient resilience to prevent compaction near the surface. Bedding, which produces a ridge of unconsolidated soil and surface organic matter, may mitigate any loss of readily exploitable soil volume caused by compaction at 20 to 25 centimeters. But bedding does not necessarily eliminate this pan or zone of compacted soil below the surface horizons. Since soil compaction may last a decade or more (Wells and Morris 1983, Miller and others 1996), a compacted zone below 20 centimeters may reduce root penetration and productivity later in the rotation.

On the basis of earlier reports (Well and Jorgensen 1978, Vitousek and Matson 1985), we expected the N-rich residues left by HFB harvesting to result in higher net soil N mineralization than MWT. Our data did not support this hypothesis. In the studies of Vitousek and Matson (1985), harvesting was followed by further disturbance of the surface soil by burning, discing, or both. When we disturbed the soil by bedding, we observed increased N mineralization but again no difference between harvesting systems was apparent.

Recently, Wilson (1994) reported a series of studies of N mineralization on the LTSP study plots in eastern North Carolina. Two years after harvesting, he could find no difference in N mineralization rate between organic removal levels ranging from a level comparable to our HFB to a complete removal of all surface organic matter to the mineral soil. Soil compaction, however, significantly reduced N mineralization.

While the amount on N contained in the branches and tops of harvested pine is considerable (table 3), over five times as much is present in the 0 to 15 centimeter layer of mineral soil (table 1). The large amounts of N mineralized during the first growing season (1995) most likely derived from root mortality and other below-ground sources. Differences in surface residue or mechanical traffic between the two harvesting systems did not influence the process. Severing the overstory forest results in a vigorous but rather brief period of N mineralization. Bedding incorporates fresh

[2] Personal communication. K. Farrish. 1996. College of Forestry, S.F. Austin State University, Nacogdoches, TX 75962.

Table 5—Total mineral (NH_4^+ + NO_3^-) captured by ion exchange resin (IER) bags during the first two growing seasons after harvesting and site preparation of a loblolly pine plantation in eastern Texas

Main treatment[a]	May/ July 95	July/ Sep 95	May/ July 96	July/ Sep 96
	Kilograms per hectare			
Hand-fell, boles only				
No added N	51.6	18.1	16.9	15.4
Added N	—	—	28.5	21.0
Mechanical whole tree				
No added N	52.1	21 .o	19.2	13.0
Added N	—	—	24.4	17.3
Not bedded				
No added N	45.1[a]	17.4	17.8	13.2
Added N	—	—	26.7	25.0
Bedded				
No added N	58.4[a]	21.7	18.4	15.3
Added N	—	—	26.2	23.6
Not fertilized	n.a.	n.a.	18.1[a]	14.2'
Fertilized	n.a.	n.a.	26.4[a]	24.3[a]

[a] The main effect of bedding was significant ($P<0.05$) for the May/July 95 monitoring period and the main effect of fertilizer was significant ($P<0.05$) for both monitoring periods in 1996. No other main effects or interactions were found to be significant at $P<0.05$.

carbon sources from the surface, increases aeration, severs and macerates root systems to a depth of 10 to 20 centimeters and increases the magnitude but not the duration of the mineralization process.

Continued monitoring to determine the long-term role of surface biomass in maintaining soil organic matter and nutrient richness is a major objective of both LTSP and MPEQ research.

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